

Hadrons from Coalescence plus Fragmentation in AA collisions from RHIC to LHC energy

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In a coalescence plus independent fragmentation approach we calculate the p_T spectra of the main hadrons: $\pi, K, p, \bar{p}, \Lambda$ in a wide range of transverse momentum from low p_T up to about 10 GeV. The approach in its main features was developed several years ago at RHIC energy. Augmenting the model with the inclusion of some more main resonance decays, we show that the approach correctly predicts the evolution of the p_T spectra from RHIC to LHC energy and in particular the baryon-to-meson ratios $p/\pi, \bar{p}/\pi, \Lambda/K$ that reach a value of the order of unit at $p_T \sim 3$ GeV. This is achieved without any change of the coalescence parameters. The more recent availability of experimental data up to $p_T \sim 10$ GeV for Λ spectrum as well as for p/π and Λ/K shows some lack of yield in a limited p_T range around 6 GeV. This indicates that the baryons p_T spectra from AKK fragmentation functions are too flat at $p_T \lesssim 8$ GeV.

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I. INTRODUCTION

Heavy-Ion collisions at ultra-relativistic energies generates the creation of a new state of matter with a temperature T significantly above the cross-over temperature $T_c \simeq 160$ MeV expected for the transition of hadronic matter to the Quark-Gluon Plasma (QGP) [1]. In the last decade a consensus seems to have emerged that quarks and gluons are indeed deconfined for a short amount of time in the fireball created, and that this quark gluon plasma behaves like a very good liquid with small viscosity over entropy density ratio η/s [2–4]. One of the most surprising observations at RHIC [52] have been the strong enhancement of the baryon over meson ratio in a wide range of $3 \text{ GeV} \lesssim p_T \lesssim 6 \text{ GeV}$ and a significantly larger (about 40 – 50%) elliptic flow v_2 of baryons with respect to that of mesons [5–7], at variance with expectation from both hydrodynamics and jet-quenching fragmentation. However soon after these first data it was realized that an hadronization process through quark coalescence can naturally explain both features of hadron spectra appearing in the same p_T region [8–15].

The idea of quark coalescence as hadronization from a QGP where the quark (anti-quark) needed to hadronize are already present and there is no need to create them from vacuum, was initially suggested in Ref.s [16, 17] with the approach known as ALCOR model. However, there the main focus was on particle yields and ratios and not the different kinematics between baryons and mesons that explains their pattern for p_T spectra and elliptic flow.

After the first papers applying the coalescence mechanism for hadron production at RHIC [8–11, 14] there have been mainly two further studies. In one case the coalescence approach has been extended to include finite width that accounts for off-shell effect which allows to include the constraint of energy conservation [18, 19]. This

is seen not to change the general feature of the coalescence mechanism, the baryon/meson enhancement and approximate quark number scaling of v_2 , but shows that at low p_T , when energy conservation plays a stronger role, a scaling with $m_T = (p_T^2 + m^2)^{1/2}$ is favored, at least for direct hadron production. More recently, an approach that from one hand enforces algebraically the unitarity similarly to ALCOR approach, but for the momentum distribution use essentially the prescription of Ref.s [9, 10] has been developed in [20, 21]. The price paid to have both aspects is the need to add a global constant in the coalescence probability in such a way that all the quarks recombine and moreover the quark distribution functions are fitted by mean of six parameters to describe hadron spectra. Nonetheless the result are similar to [9, 10] except a better description of the low p_T region, where however the present coalescence scheme can be anyway questionable and the success of the description of the spectra down to low p_T may simply come from the large flexibility of the fitted parton distribution.

In this paper, we employ the coalescence approach developed in [10, 22] that is based on the same basic idea of phase-space quark coalescence as in [11] but being solved by a Monte Carlo approach allows to include a 3D geometry as well as radial flow correlation in the partonic spectra and the effect of the main resonance decays. The last is mainly discussed in [15] and allows to have a reasonable description of the spectra also at low momenta that are usually dominated by feed-down from resonance decays. However the model does not implement a unitarity conservation that guarantees hadronization of the full bulk of particles, also energy conservation and the finite width (off-shell) effect are not included as in [18, 19] which at low momentum play a role. Therefore the model has to be considered really applicable only at $p_T \gtrsim 1.5$ GeV, even if the description of the spectra or baryon/meson ratios remains approximately good also at lower p_T , especially for pions that are dominated by decay feed-down

at low p_T . In fact the present dynamical formulation of the coalescence used remains fully meaningful when the single process of hadronization is small and hence it is not justified where the bulk of the particles resides.

We report in this paper the results applying the original model of coalescence plus fragmentation in [10] at both LHC Pb+Pb $\sqrt{s_{NN}} = 2.76$ ATeV and RHIC Au+Au $\sqrt{s_{NN}} = 200$ AGeV energies. This last case was partially present also in [10], but some more resonance decays have been added, the update Albino-Kniehl-Kramer (AKK) fragmentation function and also the Λ momentum spectra have been evaluated. Furthermore the availability of experimental data allows for a comparison in a wider p_T range. We see that the same model is able to correctly predict the spectra of the main hadrons ($\pi, K, p, \bar{p}, \Lambda$), and correctly account for the evolution of such spectra from RHIC to LHC energy and in particular the p_T dependence of the $p/\pi, \bar{p}/\pi, \Lambda/K_s^0$ ratios.

The paper is organized as follows: in Sec. II we describe the general formalism of a covariant coalescence model for mesons and baryons and how it is numerically solved by means of a Monte Carlo method. How mini-jets and the quark-gluon plasma partons are determined is described in Sec. III. Results for the transverse momentum hadronic spectra obtained from the coalescence model are given in Sec. IV for RHIC energy and in Sec. V for LHC energy. Finally, we conclude in Sec. VI with a summary of present work and an outlook about future developments and applications of the parton coalescence model.

II. COALESCENCE PLUS FRAGMENTATION MODEL

The hadronization mechanism is well known to belong to the non-perturbative domain of the QCD dynamics and certainly a first-principle description of hadron formation has yet to be obtained. One of the most common approach dealing with hadronization, routinely used in nuclear and particle physics for inclusive hadron production, is the independent fragmentation in which a single colored parton a has to hadronize into the hadron h . For this purpose, fragmentation or parton decay functions $D_a(z) \rightarrow h$ have been defined and give the probability of finding hadron h in parton a with a momentum fraction z , $0 < z < 1$. The cross section for inclusive hadron production can then be written as $\sigma_h = \sigma_a \otimes D_{a \rightarrow h}$ which is a convolution of the production cross section σ_a for parton a with the fragmentation function $D_{a \rightarrow h}(z)$. Fragmentation functions are not reliably calculable from first principles in QCD. However, they are observables and can be measured experimentally.

Physically, the fragmentation of a single parton happens through the creation of $q\bar{q}$ pairs, which subsequently arrange into color singlets forming hadrons. Such a scheme is based on the concept of QCD factorization,

which separates the long- from the short-distance dynamics. Notice that in a bulk QGP matter created in heavy-ion collisions the hadronization can occur on average at a time scale $t_h \sim 4 - 10$ fm/c (depending on its initial temperature) this means that the partons do not need a creation of $q\bar{q}$ at the moment of hadronization, but they can rescatter and generate a thermal medium expanding with a radial collective flow. At t_h partons have a certain abundance in phase space such that there is no need for the creation of additional partons through splitting or string breaking. The most naive expectation for such a scenario is a simple recombination of the deconfined partons into hadrons. Indeed, there is experimental evidence that this is the correct description of hadronization, even long before a thermal occupation of parton phase space is reached [23–26].

A. Coalescence

The approaches developed in [8, 10, 11, 27] for the coalescence is based on the Wigner formalism originally developed for nucleons [28]. The spectrum of hadrons formed from the coalescence of quarks can be written as:

$$\frac{d^2 N_H}{dP_T^2} = g_H \int \prod_{i=1}^n \frac{d^3 p_i}{(2\pi)^3 E_i} p_i \cdot d\sigma_i f_{q_i}(x_i, p_i) \times f_H(x_1 \dots x_n, p_1 \dots p_n) \delta^{(2)} \left(P_T - \sum_{i=1}^n p_{T,i} \right) \quad (1)$$

where $d\sigma_i$ denotes an element of a space-like hypersurface, g_H is the statistical factor to form a colorless hadron from quark and antiquark with spin 1/2. f_{q_i} are the quark (anti-quark) distribution in phase space. f_H is the Wigner function and describes the spatial and momentum distribution of quarks in a hadron. Eq. 1 for $i = 2$ describes meson formation, and for $i = 3$ the baryon one. The above formula can also be used for antibaryons by replacing quark momentum spectra by the momentum spectra of antiquarks

The statistical factor g_H takes into account the internal quantum numbers in forming a colorless meson from spin-1/2 colored quark and antiquark. For mesons considered here, i.e., π, ρ, ω, K , and K^* , the statistical factors are $g_\pi = g_K = 1/36$ and $g_\rho = g_{K^*} = 1/12$. For baryons and antibaryons considered in present study, i.e. p, Δ, \bar{p} and $\bar{\Delta}, \Lambda$, the statistical factors are $g_p = g_{\bar{p}} = g_\Lambda = 1/108$ and $g_\Delta = g_{\bar{\Delta}} = 1/54$. The coalescence probability function $f_M(x_1, x_2; p_1, p_2)$ ($f_H(x_1, x_2, x_3; p_1, p_2, p_3)$) depends in principle on the overlap of the quark and anti-quark distribution functions with the wave function of the meson (baryon) as well as the interactions of emitted virtual partons, which are needed for balancing the energy and momentum, with the partonic matter. Neglecting the off-shell effects the coalescence probability function is then simply the covariant hadron Wigner distribution function.

In the Greco-Ko-Levai (GKL) in Ref.[10] approach for a meson the Wigner function is a sphere of radius Δ_x in coordinate space and Δ_p in momentum space, these two parameters are related by the uncertainty principle $\Delta_x \Delta_p = 1$,

$$f_M(x_1, x_2; p_1, p_2) = \frac{9\pi}{2} \Theta(\Delta_x^2 - x_r^2) \times \Theta(\Delta_p^2 - p_r^2 + \Delta m_{12}^2)$$

where we have defined the quadri-vectors for the relative coordinates $x_{r1} = x_1 - x_2$, $p_{r1} = p_1 - p_2$ and the scalar $\Delta m_{12} = m_1 - m_2$. For a baryon we have a similar Wigner function expressed in term of appropriate relative coordinates:

$$f_B = \frac{81\pi^2}{4} \Theta\left(\Delta_x^2 - \frac{1}{2}x_{r1}^2\right) \times \Theta\left(\Delta_p^2 - \frac{1}{2}p_{r1}^2\right) \Theta(\Delta_x^2 - x_{r2}^2) \times \Theta(\Delta_p^2 - p_{r2}^2 - \Delta m_{123}^2), \quad (2)$$

and we have defined $x_{r2} = (x_1 + x_2 - 2x_3)/\sqrt{6}$ and $p_{r2} = (p_1 + p_2 - 2p_3)/\sqrt{6}$ and $\Delta m_{123} = m_1 + m_2 - 2m_3$. We note that the Wigner function for the meson has only one parameter $\Delta_p = \Delta_x^{-1}$ that we choose to have a mean square radius of mesons of about 0.8 fm which corresponds to a $\Delta_p^{meson} = 0.19$ GeV. For baryons we have also one parameter, even if one could consider two different Δ_p 's for the two relative coordinates, for qqq baryons we have a $\Delta_p^{proton} = 0.33$ GeV and for qqs baryons $\Delta_p^\Lambda = 0.38$ GeV which corresponds to a slighter smaller radius for Λ as one can expect from the wave function of an harmonic oscillator that scales with the inverse square root of the reduced mass of the system. However we have checked that small variation of Δ_p does not strongly affect the slope of the spectra coming from coalescence.

A specific feature of the GKL approach has been the inclusion of resonance decays to the pion, proton, K spectra. This was a way to include a minimal effect that certainly is present in the final spectra observed. In this paper we have also included some more resonance with respect to the original work [10] this however does not change significantly the results for the p_T spectra especially at $p_T \gtrsim 1.5$ GeV. This can be envisaged because the resonance decay products mainly feed-down the low p_T region. The residual effect at intermediate p_T can be reabsorbed by a rescaling of the Wigner function hadron parameter Δ_p by about a 10 – 15%. For the resonances the coalescence probability is augmented with a suppression factor that takes into account for the Boltzmann probability to populate an excited state of energy ΔE at a temperature T , namely accordingly to the statistical model factor $\exp(-\Delta E/T)$, with $\Delta E = E_{H^*} - E_H$ and $E_{H^*} = (p_T + m_H^*)^{1/2}$ and m_H^* the mass of the resonance; of course also the degeneracy factors that come from the different values of isospin and total angular momentum are taken in account.

B. Fragmentation

In Ref.[10, 11, 15] it has been clarified that at increasing p_T the probability to coalescence decreases and eventually the standard independent fragmentation takes over. It is therefore necessary to include also the contribution from the mini-jet fragmentation. This is done by employing the same parton distribution function that at high $p_T > p_0 \sim 3$ GeV are those that can be calculated in next-to-leading order (NLO) in a pQCD scheme. However in AA collisions one must include also the modification due to the jet quenching mechanism [29, 30]. The hadron momentum spectra from the minijet parton spectra is given by:

$$\frac{dN_{had}}{d^2p_T dy} = \sum_{jet} \int dz \frac{dN_{jet}}{d^2p_T dy} \frac{D_{had/jet}(z, Q^2)}{z^2} \quad (3)$$

where $z = p_{had}/p_{jet}$ is the fraction of minijet momentum carried by the hadron and $Q^2 = (p_{had}/2z)^2$ is the momentum scale for the fragmentation process. For $D_{had/jet}(z, Q^2)$ we employ the AKK fragmentation function [31, 32]. The fragmentation is applied for partons at $p_T > 3$ GeV. It is also worth to mention that the inclusion of both coalescence and fragmentation does not lead to a double counting of hadron formed because a hadron at p_T^h from coalescence comes from partons at $p_T \simeq p_T^h/n$ with $n = 2, 3$, while from fragmentation the parton creating it comes from a $p_T \simeq 1.5 - 2 p_T^h$. Therefore, for example considering the fragmentation for a hadron at $p_T^h \simeq 3$ GeV the quark that creates it has on average a $p_T \approx 5$ GeV but the probability of coalescence for such a parton is very small and it would produce hadrons in a very different region of $p_T^h \gtrsim 10 - 15$ GeV where the coalescence is certainly negligible.

As in [10] the multi-dimensional integrals in the coalescence formula as well as the fragmentation are evaluated by the Monte-Carlo method via test particles. Specifically, we introduce a large number of test partons with uniform momentum distribution in phase-space. To take into account the large difference between numbers of thermal and minijet partons, a test parton with momentum \mathbf{p}_T is given a probability that is proportional to the parton momentum distribution, e.g., $dN_q/d^2\mathbf{p}_T$, with the proportional constant determined by requiring that the sum of all parton probabilities is equal to the parton number. With test partons, the coalescence formulas, for mesons and baryons can be re-written as

$$\frac{dN_M}{d^2\mathbf{p}_T} = g_M \sum_{i,j} P_q(i) P_{\bar{q}}(j) \delta^{(2)}(\mathbf{p}_T - \mathbf{p}_{iT} - \mathbf{p}_{jT}) \times f_M(x_i, x_j; p_i, p_j). \quad (4)$$

and

$$\begin{aligned} \frac{dN_B}{d^2\mathbf{p}_T} &= g_B \sum_{i \neq j \neq k} P_q(i) P_q(j) P_q(k) \\ &\times \delta^{(2)}(\mathbf{p}_T - \mathbf{p}_{iT} - \mathbf{p}_{jT} - \mathbf{p}_{kT}) \\ &\times f_B(x_i, x_j, x_k; p_i, p_j, p_k). \end{aligned} \quad (5)$$

In the above, $P_q(i)$ and $P_{\bar{q}}(j)$ are probabilities carried by i th test quark and j th test antiquark.

The Monte-Carlo method allows us to treat the coalescence of low momentum partons on the same footing as that of high momentum ones.

III. FIREBALL AND PARTON DISTRIBUTIONS

The coalescence approach as developed till now to describe hadron production in uRHIC's is based on a fireball where the bulk of particles is a thermalized system of gluons and u, d, s quarks and anti-quarks at the temperature $T_c = 165 \text{ MeV}$ [1] which is about the temperature for the cross-over transition in realistic lattice QCD calculation [34]. At high momenta, $p_T > 2.5 \text{ GeV}$, the distribution is taken to be the partonic spectra that undergone the in-medium jet quenching [33]. The longitudinal momentum distribution is assumed to be boost-invariant, i.e., a uniform rapidity distribution in the range $y \in (-0.5, +0.5)$. While these features are common to both RHIC and LHC, with the beam energy there is a change in the radial flow and self-consistently in the volume of the bulk of the QGP, as well as at high p_T there is a different initial distribution and jet quenching.

In this paper, we consider Au+Au at $\sqrt{s_{NN}} = 200 \text{ GeV}$ at RHIC and Pb+Pb collision at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ at the Large Hadron Collider (LHC) for the central collisions (0 – 10%). To take into account for the quark-gluon plasma collective flow, we assume for the partons a velocity linear radial profile as $\beta_T = \beta_{max} \frac{r}{R}$, where R is the transverse radius of the fireball. The quark and antiquark distribution up to 2 GeV are hence given by a thermal distribution with flow:

$$\frac{dN_{q,\bar{q}}}{d^2r_T d^2p_T} = \frac{g_{q,\bar{q}} \tau m_T}{(2\pi)^3} \exp \left(-\frac{\gamma_T(m_T - p_T \cdot \beta_T \mp \mu_q)}{T} \right) \quad (6)$$

here $g_q = g_{\bar{q}} = 6$ indicates the spin-color degeneracy of light quarks and antiquarks, and the minus and plus signs are for quarks and antiquarks, respectively. The temperature is set to $T = 165 \text{ MeV}$. Eq. (6) also applies to gluons after replacing g_q by the gluon spin-color degeneracy $g_g = 16$ and dropping the chemical potential. For the gluon mass, we take it to be similar to that of light quarks in order to take into account non-perturbative effects in the quark-gluon plasma. Because $m_g < 2m_q$, we convert $gq \rightarrow q\bar{q}$. Positions of partons in the transverse direction are taken to have a uniform distribution. Their longitudinal positions are then determined by $z = \tau \sinh y$, as we have assumed Bjorken correlation $\eta = y$.

The radial flow β_{max} and the volume $V = \pi R_\perp^2 \tau$ (in one unit of rapidity) could be in general considered as parameters evaluated accordingly to the typical value of lifetime of the QGP and, assuming a constant acceleration, we connect the radial expansion with the radial flow $R_\perp = R_0 + 0.5\beta_{max}\tau$. So the radial flow and the volume are constrained imposing the total multiplicity dN/dy and the total transverse energy dE_T/dy to be equal to the experimental data. The charged particles multiplicity per unit of rapidity is $dN_{ch}/dy \simeq 1600$ and the transverse energy $dE_T/dy = 2100 \text{ GeV}$ at LHC, $dN_{ch}/dy \simeq 670$ and $dE_T/dy = 760 \text{ GeV}$ at RHIC. This leads for a radial uniform expansion to $\beta_{max} = 0.37$ and $R_\perp = 8.7 \text{ fm}$, $\tau = 4.5 \text{ fm}/c$ at RHIC, and $\beta_{max} = 0.60$ and $R_\perp = 10.2 \text{ fm}$, $\tau = 7.8 \text{ fm}/c$ at LHC in quite good agreement also with simulations in hydrodynamical or kinetic transport approaches. We notice that such a values correspond in one unity of rapidity to a volume of $V \sim 1100 \text{ fm}^3$ at RHIC, while at LHC $V \sim 2500 \text{ fm}^3$, which means an increase of a bit more than a factor of two in agreement with the estimate from pion HBT interferometry [35].

The baryon chemical potential for quarks $\mu_b = \mu_B/3$ is set to reproduce the p/\bar{p} ratio observed experimentally which means $\mu_b = 10 \text{ MeV}$ at RHIC while at LHC we have approximated μ_b to zero. As in Ref.s [9, 10] the quark and antiquark masses considered are $m_{d,u} = m_{\bar{d},\bar{u}} = 330 \text{ MeV}$ for light quarks, and $m_s = m_{\bar{s}} = 450 \text{ MeV}$ for strange quarks. This implies a number of quarks per unit of rapidity within the fireball at RHIC is $N_{u,d} \sim 230$, $N_{\bar{u},\bar{d}} \sim 210$ and $N_{s,\bar{s}} \sim 150$. At LHC there are $N_{u,\bar{u},d,\bar{d}} \sim 530$ and $N_{s,\bar{s}} \sim 360$. We also notice that despite the quite different total energy at both RHIC and LHC the energy density of the fireball (with radial flow energy subtracted) is about $\epsilon \simeq 0.7 \text{ GeV}/\text{fm}^3$ in good agreement with the energy density at T_c as evaluated in lattice QCD studies [34].

For partons at high transverse momentum, $p_T > 2.5 \text{ GeV}$ (see previous Section), we consider the minijets that have undergone the jet quenching mechanism. Such a parton distribution can be obtained from pQCD calculations. As in Ref.[10] we have considered the initial p_T distribution according to the pQCD and the thickness function of the Glauber model to go from pp collisions to AA ones. Then we have quenched the spectra with the modeling as in Ref. [33] to reproduce the p_T spectrum of pions as observed experimentally at $p_T \sim 8 \text{ GeV}$. These parton spectra can be parametrized at RHIC as

$$\frac{dN_{jet}}{d^2p_T} = A \left(\frac{B}{B + p_T} \right)^n \quad (7)$$

which is the same used in [9, 10] with the values given in the TableIII. The parametrization at LHC is

$$\frac{dN_{jet}}{d^2p_T} = \frac{A_1}{\left[1 + \left(\frac{p_T}{A_2} \right)^2 \right]^{A_3}} + \frac{A_4}{\left[1 + \left(\frac{p_T}{A_5} \right)^2 \right]^{A_6}} \quad (8)$$

with the values of A_i given in TableIII

	$A[1/GeV^2]$	$B[GeV]$	n
g	$3.18 \cdot 10^4$	0.5	7.11
u, d	$9.79 \cdot 10^3$	0.5	6.84
\bar{u}, \bar{d}	$1.89 \cdot 10^4$	0.5	7.59
s	$6.51 \cdot 10^3$	0.5	7.36
\bar{s}	$8.02 \cdot 10^3$	0.5	7.57

TABLE I: Parameters for minijet parton distributions at midrapidity from Au+Au at $\sqrt{s} = 200 AGeV$

	A_1	A_2	A_3	A_4	A_5	A_6
g	23.46	4.84	8.08	2.78	2.79	2.31
u, d	24.68	5.11	8.01	0.55	5.65	2.56
\bar{u}, \bar{d}	23.12	5.05	8.21	0.57	5.62	2.58
s	24.14	5.11	8.01	0.55	5.65	2.56
\bar{s}	23.12	5.00	8.31	0.57	5.62	2.61

TABLE II: Parameters for minijet parton distributions at midrapidity from Pb-Pb at $\sqrt{s} = 2.76 ATeV$

IV. HADRON SPECTRA AND RATIOS AT RHIC

In this section, we show results for the transverse momentum spectra of pions, protons, antiprotons, kaons and Lambdas using the model described in previous sections. For the coalescence contribution, we first take into account the effects due to gluons in the quark-gluon plasma by converting them to quarks and anti-quark pairs with probabilities according to the flavor compositions in the quark-gluon plasma, as assumed [10, 16]. For both mesons and baryons, we include not only coalescence of hard and soft partons as in Ref.[10] but also that among soft hard partons which are relevant for hadrons at $p_T \simeq 3 - 4 GeV$. Furthermore, we include both stable hadrons such as pion, proton (anti-proton), and kaon (anti-kaon) as well as the first excited resonances. With respect to [10] we have added some more resonance which has allowed also to verify that the inclusion of resonances improves the description especially at low p_T but does not affect significantly the intermediate p_T and the baryon/meson ration around the peak.

For the pion ($I = 1, J = 0$) spectrum the following resonance and their decay channels are included: K^* ($I=1, J=1/2$) with $K^* \rightarrow K\pi$; ρ ($I=1, J=1$) with $\rho \rightarrow \pi\pi$; ω ($I=0, J=1$) with $\omega \rightarrow \pi\pi\pi$; Δ ($I=3/2, J=3/2$) with $\Delta \rightarrow N\pi$. In Fig. 1 it is shown the predicted for the coalescence plus fragmentation π^0 distribution in p_T for RHIC in Au+Au collisions at $\sqrt{s} = 200 GeV$ for (0 – 10%) centrality; the experimental data are shown by circles [36] and triangles [37]. We can see a general good agreement for $p_T > 1 GeV$ that is about the region where we expect the coalescence plus fragmentation approach to apply. In Fig.1 we show much more details of the calculation. By thin solid line and dashed line it is

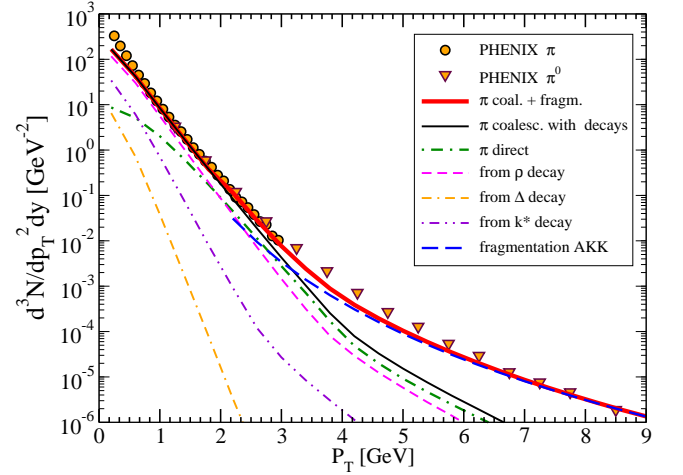


FIG. 1: Pion transverse momentum spectrum at RHIC in Au+Au collisions at $\sqrt{s} = 200 AGeV$, 0 – 10% centrality. Pion production from coalescence shown by thin solid line. Direct pions are shown by the dash-dotted line. Pion from resonance decay are dashed lines for ρ ; dash double-dot line for K^* ; double-dashed dot line for Δ . Pion from mini-jet fragmentation are the dashed line. Sum of both hadronization processes shown by thick solid line). Experimental data from PHENIX [36] [37].

plot the contribution from pure coalescence and fragmentation respectively. We can see that the contribution of both mechanism becomes about similar for $p_T \simeq 3.5 GeV$ and we will see that for the baryon instead the coalescence will dominate in a large p_T range. We can also see the contribution for the decay into pions coming from resonances, which shows that contribution from $\rho \rightarrow \pi\pi$, dashed line, dominates up to about $p_T \sim 3 GeV$ which is about the region where anyway the fragmentation is starting to take over. The contribution from K^* (dashed double-dotted line) and Δ (double-dashed dot line) are instead quite less relevant and only contribute to some little improvement of the description at very low p_T . Of course for the pions it is know more or less all the hadrons contribute to the feed-down, see also Ref.[38], but in the region we are interested in the resonances included are sufficient to have a good description of the pion spectra at $p_T \gtrsim 1 GeV$, see Fig.1.

For the proton (anti-proton) ($I=1/2, J=1/2$) we have included the Δ ($I=3/2, J=3/2$) with its decay, $\Delta \rightarrow N\pi$, but we have also checked that adding the next excited state $N(1440)$ ($I=1/2, J=1/2$) production and decay leads to negligible contribution due to the large suppression factor but also to the fact that about 40% of the decay goes through $N(1440) \rightarrow N\pi\pi$ which means that the proton spectrum coming from $N(1440)$ is quite steep and gives some contribution only at quite low $p_T \lesssim 0.5 GeV$. In Fig. 2 we show the anti-proton transverse momentum spectrum at RHIC including coalescence and fragmentation by thick solid line together with the available experimental data (circles) from Ref.s

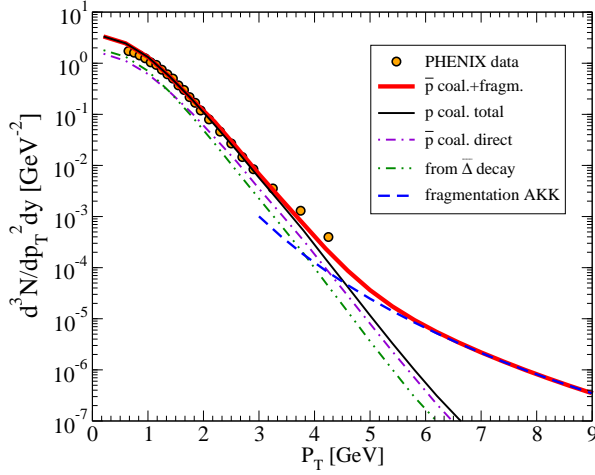


FIG. 2: Antiproton transverse momentum spectrum at RHIC in Au+Au collisions at $\sqrt{s} = 200$ AGeV, 0 – 10% centrality. Antiproton production from coalescence thin solid line. Direct antiproton are shown by the violet dash-dotted line; from Δ decay are the dash double-dotted line. Antiproton from minijet fragmentation are the dashed line. Sum of both hadronization processes shown by thick solid line. Experimental data from PHENIX [36].

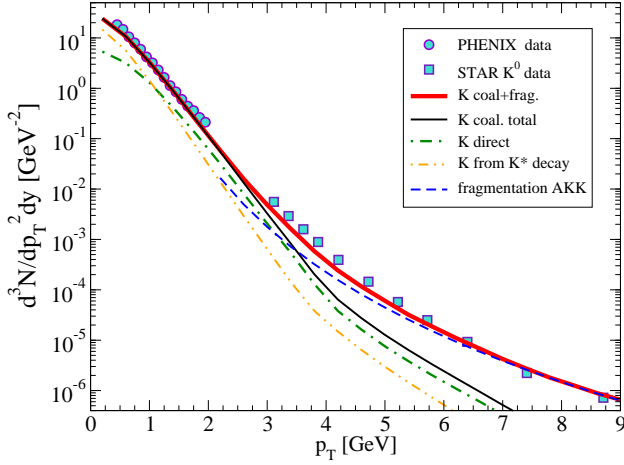


FIG. 3: Kaon transverse momentum spectrum at RHIC in Au+Au collisions at $\sqrt{s} = 200$ AGeV, 0 – 10% centrality. Kaon production from coalescence is the thin solid. Direct kaons are shown by the dash-dotted line. Kaons from K^* decay are the dash-double-dotted line. Kaon from mini-jet fragmentation is the dashed line. Sum of both hadronization processes is shown by thick solid line. Experimental data from PHENIX [36] are shown by the circles, STAR [39] data are shown by the squares.

[36]. Again the description appears to be quite good; we show also the relative contribution from coalescence and fragmentation by thin solid line and by dashed line respectively. We notice that for anti-protons the two mechanism become comparable at $p_T \simeq 5$ GeV which means that the coalescence contribution is more important for protons with respect to pions.

In Fig. 3 we show also the p_T distribution for the K^\pm ($I=0$, $J=1/2$) for which we have included the $K^*(892)$ ($I=1$, $J=1/2$) contribution from the decay of $K^* \rightarrow k\pi$. The impact of the next excited state $K_1(1270)$ is again negligible especially at $p_T \gtrsim 1$ GeV. We can see that also for Kaons the agreement with experimental data from PHENIX at low p_T [36], open circles, and STAR [39], squares, is fairly good in all the range of p_T . By dash double dotted line in Fig.3, we see that at low p_T the contribution from K^* decay becomes important and contributes to have the correct slope of the spectrum as measured experimentally. One can notice as in the case of pions that there is some lack of yield at $p_T \simeq 4$ GeV where the fragmentation is starting to be dominant. We anticipate that such a systematic is observed also at LHC and from the ratio baryon/meson we will see that it is even more marked for baryons and in particular for Lambda's. The p_T distribution for $\Lambda(1116)$ ($I=0$, $J=1/2$) at RHIC

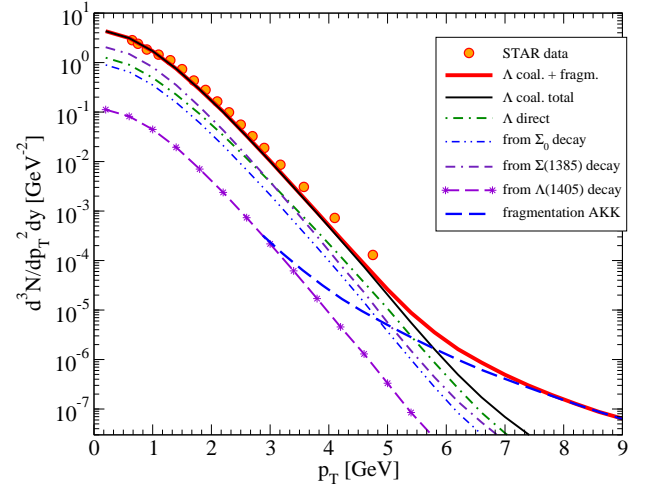


FIG. 4: Λ transverse momentum spectrum at RHIC in Au+Au collisions at $\sqrt{s} = 200$ GeV, 0 – 10% centrality. Λ production as sum of both hadronization processes is shown by thick solid line; from coalescence only by thin solid line. Direct Λ s are shown by the dash-dotted line. Λ from resonance decay are: Σ^0 (dashed double dotted line), $\Sigma(1385)$ (double dashed dotted line), $\Lambda(1405)$ (dashed line with * symbols). Λ from mini-jet fragmentation is the dashed line. Experimental data from STAR [40].

energy in Au+Au collisions at $\sqrt{s} = 200$ GeV for central collisions is shown in Fig. 4 by thick solid line along with the experimental shown by circles [40]. For the Λ there are indeed several hadronic states that have a significant contribution and we have included the following closest resonances with their decay channels and the pertinent branching ratios (B.R.): $\Sigma_0(1193)$ ($I=1$, $J=1/2$); $\Sigma_0 \rightarrow \Lambda\gamma$, $\Lambda(1405)$ ($I=0$, $J=1/2$); $\Lambda(1405) \rightarrow \Sigma\pi$, $\Sigma(1385)$ ($I=1$, $J=3/2$) with the two main decay channels: $\Sigma(1385) \rightarrow \Lambda\pi$ with $B.R. = 88\%$ and $\Sigma(1385) \rightarrow \Sigma\pi$ with $B.R. = 11.7\%$. In Fig. 4 one can also find the different contribution of these channel, see also the caption. Also for the Lambda the coalescence plus fragmentation

model appear to be able to correctly described the experimental data in a wide range of p_T . We also find similarly to the anti-proton that the contribution from independent fragmentation according the AKK parametrization becomes dominant at $p_T \gtrsim 6$ GeV.

The coalescence mechanism has had the merit to naturally predict a baryon/meson enhancement at intermediate transverse momentum, especially in the region $p_T \simeq 2 - 4$ GeV where the p/π^+ , \bar{p}/π^- , $\Lambda/2K_s^0$ reaches a value of the order of unity which is a strong systematic enhancement with respect to the one observed in pp collisions [15].

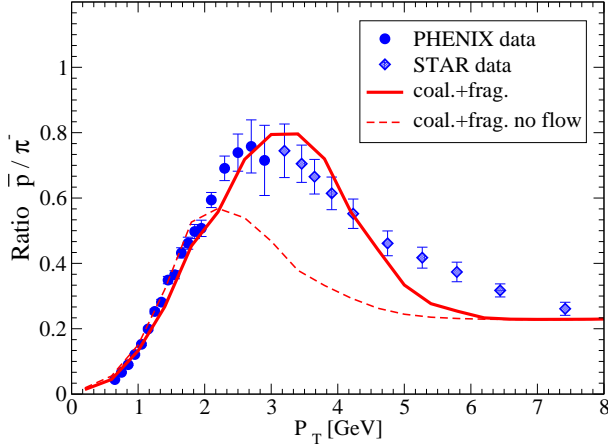


FIG. 5: Anti-Proton to positive pion ratio at RHIC from Au+Au collisions at $\sqrt{s} = 200$ GeV. The model prediction is the thick solid line; by dashed line the result switching off the radial flow of the QGP bulk matter. PHENIX [36] data are shown by circles, STAR [39] data by triangles.

We therefore show the \bar{p}/π^- , Λ/K_s^0 in the Figs. 5 and 6. We can see that the ratio is quite well predicted from its rise at low p_T up to the peak region and then the falling-down behavior. However in both cases it is clear that in the region of $p_T \simeq 5 - 7$ GeV there is a lack of baryon yield. This is a feature that could not be observed when the coalescence+ fragmentation model was applied a decade ago to hadronization at RHIC because there were no data available for proton (anti-proton) at $p_T > 4$ GeV, nonetheless it appears systematically, we will see it also at LHC energy, so we postpone some further comment about it at the end of the next Section.

V. HADRON SPECTRA AND RATIOS AT LHC

We present in this Section the results from the coalescence plus fragmentation and the comparison with the experimental data for Pb+Pb collisions at $\sqrt{s} = 2.76$ ATeV for 0 – 10% collisions. We notice that the results are obtained without any change or addition of parameters with respect to the one at RHIC in the previous Section. Indeed a main aim of the present paper is to show that the evolution of the baryon/meson pattern

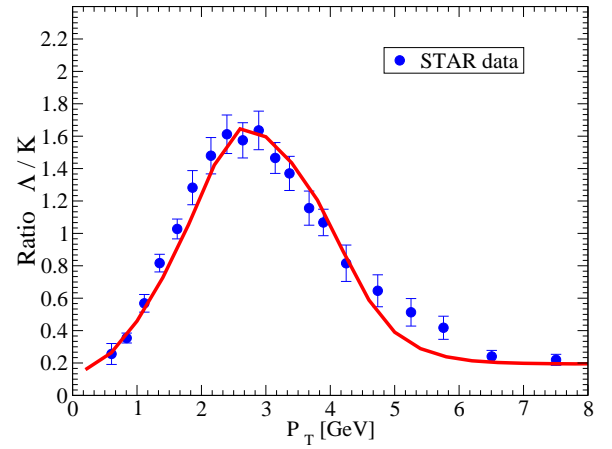


FIG. 6: Lambda to kaon ratio at RHIC from Au+Au collisions at $\sqrt{s} = 200$ AGeV. The model prediction is the solid line. STAR data by circles [41].

from RHIC to LHC can be correctly and self-consistently predicted. The only change with respect to RHIC is in the radial flow and volume of the hadronizing fireball that as described above is self-consistently constrained but the total transverse energy and the multiplicity that at LHC $\sqrt{s} = 2.76$ ATeV is about a factor 2.4 and 2.7 larger with respect to RHIC $\sqrt{s} = 200$ AGeV, see Section III-a.

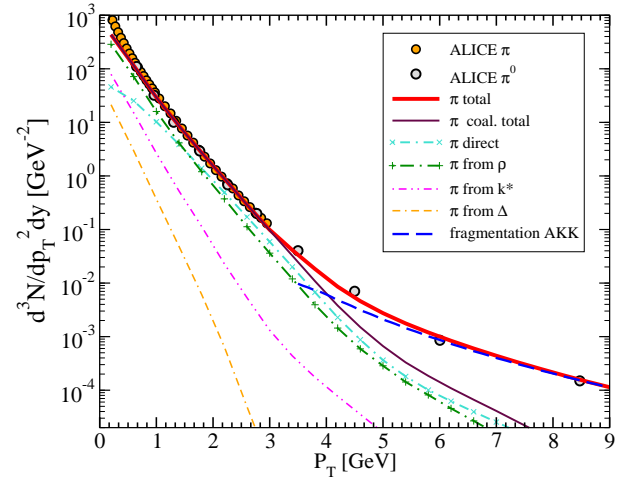


FIG. 7: Pion transverse momentum spectrum from Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV, 0 – 10% centrality. The solid curve includes contributions from coalescence process. The thick solid line is the sum of coalescence and fragmentation contributions. Direct pions are shown by the dash-dotted line with X symbols. Pion from resonance decay are the dash-dotted lines with "+" symbol for ρ , dashed double-dotted lines for K^* , double-dashed dotted line for Δ . Pions from mini-jet fragmentation are the dashed line. The circles are the experimental data from ALICE experiment [42] [43].

In Fig.7 we show the total (coalescence + fragmentation) pion spectrum by thick solid line which is a quite good agreement with the experimental data on π^0 from

ALICE Collaboration in all the p_T range, except some lack of yield at $p_T \lesssim 0.5$ GeV due to absence of all the resonance decays feed-down. By thin solid and dashed line we show the contribution from coalescence and fragmentation respectively. We notice that the two yields cross at $p_T \simeq 4$ GeV which is about a shift of about 1 GeV with respect to RHIC, see Fig. 1 such a shift is due to the larger collective flow present at LHC that shifts to larger p_T the hadrons from coalescence. The very good agreement of the p_T distribution at LHC already shows that the model is able to correctly predict the evolution of the absolute yield and especially its p_T shape correctly, in fact no parameter of the coalescence process, essentially the Wigner wave function width Δ_p of the hadrons, has been modified with respect to those used in the previous Section for RHIC.

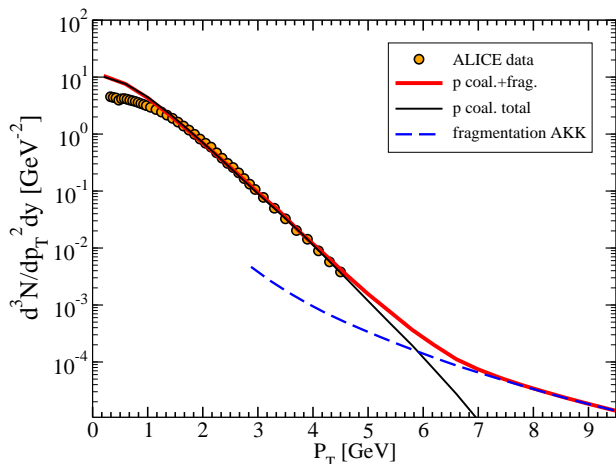


FIG. 8: Proton transverse momentum spectrum from Pb+Pb collisions at $\sqrt{s} = 2.76$ ATeV, 0 – 10% centrality. The solid thick line is the sum of coalescence and fragmentation process. The solid thin curve shows the contribution from coalescence. Protons from minijet fragmentation are the dashed line. The circles are the experimental data from ALICE experiment [42].

In Fig.8 it is shown the proton spectrum at LHC by thick solid line and compared to the experimental data. The agreement also in this case is very good for $p_T > 1$ GeV up to 5 GeV that is the maximum value with available data. At very low p_T as said in Section II we should not expect the approach to really apply. Still we can notice that the coalescence over predict the yield. The effect was partially present also at RHIC, see Fig. 2. The larger discrepancy at LHC could be in agreement with a larger annihilation of p and \bar{p} that can be expected to be larger with respect to RHIC and could explain the disagreement between the statistical model prediction and the experimental data.

In Fig.8 we can also see that the yield of the fragmentation process becomes comparable to the one from coalescence at a $p_T \simeq 6$ GeV which is about a 50% larger with respect to the pions and also a shift of about 1.5 GeV with respect to RHIC. This is what one would ex-

pect due to the larger flow at LHC and the fact that baryons are more affected by it.

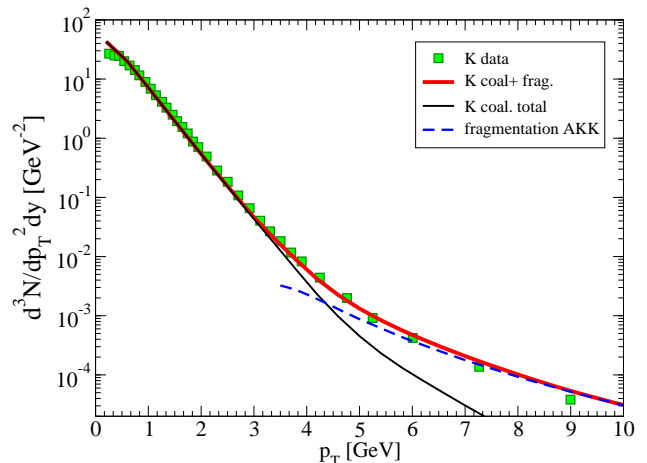


FIG. 9: Kaon transverse momentum spectrum from Pb+Pb collisions at $\sqrt{s} = 2.7$ ATeV, 0 – 10% centrality. The dashed curve includes contributions from coalescence process. The thick solid line is the sum of coalescence and fragmentation contributions. Kaons from mini-jet fragmentation are the dashed line. The squares are the experimental data from ALICE experiment [42, 44, 45].

In Fig.9 the p_T distribution for K^+ is shown by thick solid line and again one can see the good agreement with the experimental data [45] in the entire range of p_T . We can notice that at RHIC for both pions and kaons there was some lack of yield in the region where the fragmentation takes over, while at LHC energy for both cases the agreement appears quite better. This can be expected because the independent fragmentation function picture should be better constrained at energies of the order of TeV.

In Fig.10 the experimental data for the transverse momentum spectrum of Λ is shown by circles together with the results from the coalescence plus fragmentation shown by thick solid line. The different contribution from excited state have been calculated and have a similar relative contribution as at RHIC, see Fig.4 We can see also for this case the good agreement for $p_T > 1$ GeV, but while for p and \bar{p} the data are available only up to 4-5 GeV, in this case we have the availability of data up to 9 GeV and this allows us to see that in the p_T region where the fragmentation starts to dominate, $p_T \simeq 6 - 7$ GeV there is some lack of yield. This something that we could only marginally spot at RHIC energy mainly through the Λ/K ratio, see Fig. 6. At both RHIC and LHC such a lack of yield appears where coalescence becomes less important therefore one can say that it seems that the spectrum from AKK fragmentation function appears too flat. This may very well be because the fragmentation function for baryons in general and in particular for Λ are known to be not very well constrained. On the other hand we notice that the fragmentation contribution has been calculated for all hadrons considered with

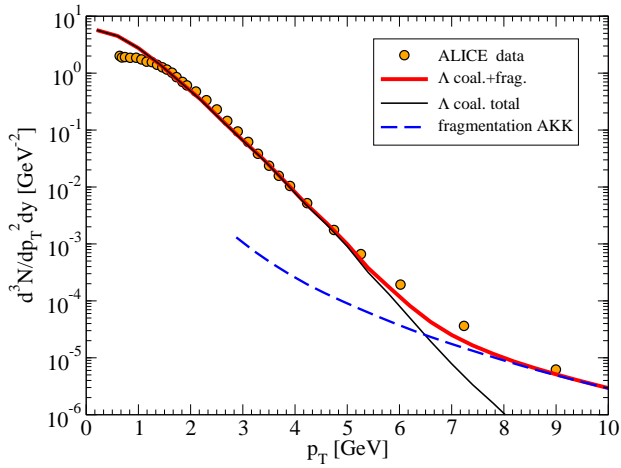


FIG. 10: Λ transverse momentum spectrum from Pb+Pb collisions at $\sqrt{s} = 2.76$ ATeV, 0 – 10% collisions. The thin solid curve includes all contributions from coalescence process. Λ from mini-jet fragmentation is the dashed line. The sum of coalescence and fragmentation contributions is shown by the thick solid line. The circles are the experimental data from ALICE experiment [44] [45].

the same $Q^2 = (p_{had}/2z)^2$ and this gives a global good description of the spectra for π, K at $p_T > 5$ GeV and for p, \bar{p}, Λ for $p_T > 8$ GeV. However we mention that a similar problem has been recently pointed-out also in pp collisions in Ref.s[46]; also it seems that the KKP fragmentation can supply a better description even if still not satisfying. We also notice that in pp collisions the fragmentation function gives an excess of yield increasing with p_T while in AA such an effect is hidden by the large jet quenching that is tuned to reproduce the pion spectra at $p_T \simeq 8$ GeV. On the other it still appears as a too flat spectrum at $p_T \sim 3 - 8$ GeV. In AA collisions it is likely that studies of in-medium fragmentation function can find a solution [47, 49] or it could be that coalescence contribution should extend to large p_T with respect to the present modeling having simple spheres in momentum space as Wigner function and no dynamical role of the interaction that could lead to an extension of the coalescence to pair with larger relative momentum.

We mention that recently it has been developed a process that within the coalescence plus fragmentation approach could be quite important in solving this issue [49]. The idea is to describe the in-medium fragmentation as a quark recombination of shower partons taking into account also the gluon splitting into quark pairs that recombine. Such a mechanism seems to provide a large contribution for baryons in the region of $p_T \sim 6$ GeV [50].

In Fig.11 we compare the p/π ratio vs p_T shown by solid line with the experimental data of the ALICE Collaboration [48] shown by open circles. The description is overall quite good with some quite limited lack of proton yield at $p_T \sim 6$ GeV. In Fig.5 it is also shown by dashed line the p/π ratio if the coalescence between soft

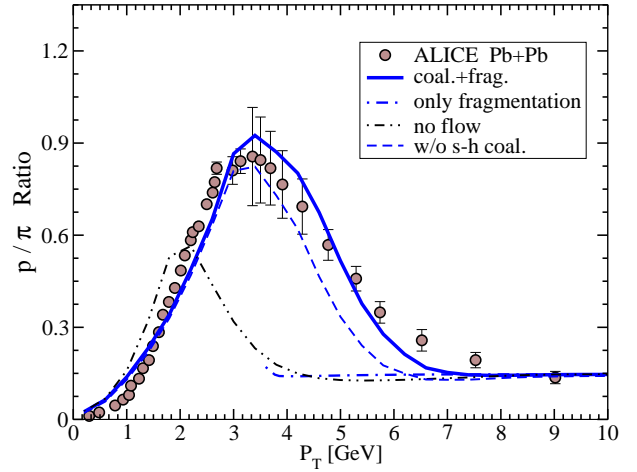


FIG. 11: Proton to pion ratio in Pb+Pb collisions at $\sqrt{s} = 2.76$ ATeV. The solid line is the prediction of our model. The empty circles are data from ALICE experiment in collision Pb+Pb at 0-5% centrality [48].

partons from the QGP and a mini-jet. We can see that the contribution is significant for $p_T > 3$ GeV. The impact of radial flow of the soft partons is shown by dashed

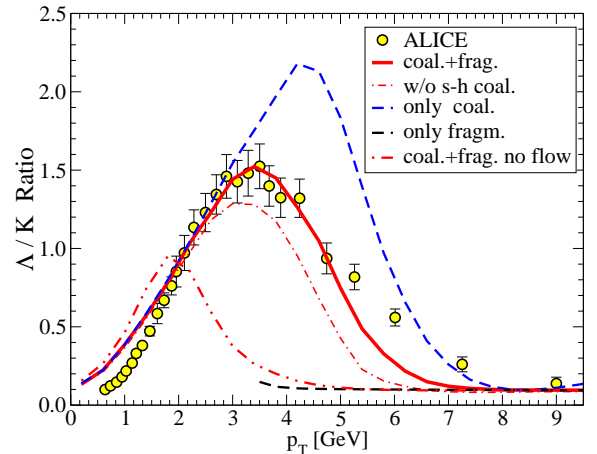


FIG. 12: Lambda to kaon ratio in Pb+Pb collisions at $\sqrt{s} = 2.7$ ATeV. The solid line is the prediction of our model. The circles are data from ALICE experiment in collision Pb+Pb at 0-5% centrality. [44]

In Fig. 12 we show the results for the Λ/K ratio in comparison with the experimental data shown by circles [44]. We can see generally a good overall description of the ratio especially in the region of the peak. Comparing the dashed-dot line with the thick solid line we can see that in the peak region a quite good agreement with the experimental data is reached thanks to a recombination of thermal soft partons with a mini-jet parton. The relevance of such a process is present also in the EPOS approach Ref.[47], and it is an idea that can be traced back to ref.[51] However as discussed above at $p_T \sim 6$ GeV there

is a significant lack of Λ yield that here in a linear scale appears quite large. A tendency to underestimate the yield is visible also in [47] even if quite smaller thanks to a different fragmentation scheme with respect to AKK. The low ratio is only slightly low because of the large K yield in this p_T range, see Fig.9, and most of the disagreement with the data comes from the lack of yield in the Λ 's distribution from fragmentation that appears too soft in this p_T range. In Fig.12 we also show the behavior of the Λ/K ratio if only coalescence is considered, dashed line, or if only fragmentation is included.

VI. SUMMARY AND CONCLUSIONS

In this paper, we have studied the hadronization of the quark-gluon plasma and mini-jet partons produced in relativistic heavy ion collisions in terms of the parton coalescence plus fragmentation model. The p_T distributions of partons in the quark-gluon plasma is taken to have an exponential form with a temperature similar to the phase transition temperature, $T_c \simeq 160$ MeV but boosted by a radial flow β . The volume and radial flow of the hadronizing QGP are constrained by the total multiplicity and total transverse energy. Partons at higher $p_T \simeq 15 T_c \simeq 2.5$ GeV are taken to be the minijets with power-law spectra that have undergone the jet-quenching process. The approach is in its core the one developed at RHIC energy a decade ago [10]

The aim has been to investigate if the approach already successful a decade ago with the first RHIC data was able to correctly predict the evolution of the transverse momentum spectra from RHIC to LHC energy. More specifically the new data also at RHIC have been available in a wider p_T range especially for the baryon-to-meson ratio and at LHC it has become possible to verify the approach in a wider p_T range up to about 10 GeV also for the Λ and for both the p/π and Λ/K ratio. We found a quite good agreement of both the p_T spectra for the main hadrons like $\pi, K, p, \bar{p}, \Lambda$ and the baryon-to-meson ratio $p/\pi, \Lambda/K$ in a wide region of p_T up to about 10 GeV. The yield and slope of the spectra as well as for the height and p_T positions of the peak in the baryon/meson ratio is correctly predicted. This is achieved without any adjustment of the coalescence parameter Δ_p for mesons and baryons and hence can be considered as a real prediction of the model. We also note that underlying such agreement a key ingredient is the radial flow of the QGP matter. A coalescence model without radial flow could not account for properly neither for the baryon over meson enhancement nor for the single p_T hadron spectra.

With respect to the original paper [10] the new data extends to higher p_T , especially for the Λ , and this as allowed to spot some lack of yield for baryons in the p_T region where the coalescence contribution is dying out and fragmentation is taking over, which means at $p_T \sim 6$ GeV. It appears that the independent fragmentation approach gives too hard spectra at least up to $p_T \sim 8$ GeV especially for baryons, similarly to what has been pointed out for charged hadrons in pp collisions [46]. In AA collisions this result seems to point to the need of an in-medium fragmentation process in agreement with the first results of a shower recombination of quarks from gluon decays [49, 50].

We remind that the coalescence has played an important role in the discussion about the QGP properties not only thanks to the explanation of the baryon/meson enhancement but also because of the approximate quark number scaling observed at RHIC and suggested by a simplified approach to a pure coalescence mechanism [14]. A more realistic approach to coalescence in three dimension with radial flow correlations, finite hadronic wave function widths and resonance decays shows that about a 10% breaking has to be expected at intermediate p_T , and quite larger one at low p_T [22, 38] correctly predicting the experimental observation [5]. At LHC energy experimental data show a larger breaking of the scaling with respect to the one observed at RHIC or predicted by more realistic coalescence models. However we note that the data discussed now are based on event-by-event analysis that shows the presence of higher harmonics like v_3, v_4, v_5 which also have a quite large variance. This can be expected to further break the naive quark number scaling of the $v_2(p_T)$ but a quantitative approach requires an extension of the present approach to an event-by-event Monte Carlo one. Such an approach is currently under development and it requires a significant longer computational effort to have a good statistical mapping of the various harmonics $v_n(p_T)$ in each event and in a wide range of p_T . However the present work, showing that also at LHC the main hadronic p_T spectra and baryon-to-meson ratios are well predicted, provides the motivation to extend the study to the anisotropic flows.

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